

A comparative analysis of configurations of linear Fresnel collectors for concentrating solar power

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A B S T R A C T

Linear Fresnel collector arrays present some relevant advantages in the domain of concentrating solar power because of their simplicity, robustness and low capital cost. However, they also present important drawbacks and limitations, notably their average concentration ratio, which seems to limit significantly the performance of these systems.

First, the paper addresses the problem of characterizing the mirror field configuration assuming hourly data of a typical year, in reference to a configuration similar to that of Fresdemo. For a proper comparative study, it is necessary to define a comparison criterion. In that sense, a new variable is defined, the useful energy efficiency, which only accounts for the radiation that impinges on the receiver with intensities above a reference value. As a second step, a comparative study between central linear Fresnel reflectors and compact linear Fresnel reflectors is carried out. This analysis shows that compact linear Fresnel reflectors minimize blocking and shading losses compared to a central configuration. However this minimization is not enough to overcome other negative effects of the compact Fresnel collectors, as the greater dispersion of the rays reaching the receiver, caused by the fact that mirrors must be located farther from the receiver, which yields to lower efficiencies.

Keywords:

Linear Fresnel collectors

Optical optimization

Useful energy efficiency

Compact linear Fresnel collectors

1. Introduction and background

Main advantages of LFC (linear Fresnel collectors) are its simplicity, robustness and low capital cost, as well as the degrees of freedom one finds in the design process, which must be analyzed in depth for reaching the maximum outcome in the variable representing the plant performance.

On the contrary, from the annual performance perspective they seem to reach lower efficiencies than parabolic trough collectors, as it is showed in the technical literature [1–4]. Performance losses in LFC systems may be classified into optical and thermal ones. Similarly to parabolic trough, optical losses are comparatively much higher than thermal losses, for conventional working temperatures below 400 °C. Although the main drawback of the LFC systems is their low optical efficiency, this paper attempts to demonstrate that an adequate optical characterization considering a new variable, the useful energy efficiency, would imply a significant improvement in the overall performance of the LFC system.

There are multiple LFC designs in the literature. Both the receiver and the primary mirrors field have many degrees of freedom that can be characterized and optimized. Although this paper focuses on an optical study, the next section provides a review of both thermal and optical aspects.

1.1. A review on different linear Fresnel collector designs

Although almost all recent commercial STPP (Solar Thermal Power Plants) are parabolic trough plants, it seems that linear Fresnel collectors are becoming an attractive option to generate electricity from solar radiation.

There are already several LFC commercial plants and prototypes for power generation installed in different countries, like Puerto Errado 1 (1.4 MW_e) and Puerto Errado 2 (30 MW_e) in Spain, Kimberlina (5 MW_e), in California (USA), Augustin Fresnel 1 (250 kW_e) in France, and CNIM (1 MW_e) in France [5–11]. In addition to the previous plants, which are coupled directly to a Rankine cycle, there is a Fresnel plant integrated in the Liddell coal fired power station in Australia, which provides saturated steam to the conventional plant [12]. Table 1 summarizes the main characteristics of every LFC plant.

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Nomenclature

Symbols

$A_{\text{primary mirrors}}$ (m^2)	primary mirrors surface area
$A_{\text{solar field}}$ (m^2)	total solar field surface area (including gaps between mirrors)
$A_{\text{shaded, primary mirrors}}$ (m^2)	shaded area of primary mirrors surface
$A_{\text{blocking, primary mirrors}}$ (m^2)	blocking suffering area of primary mirrors surface
CLFC	compact linear Fresnel collector
CPC	Compound Parabolic Collector
DNI (W/m^2)	Direct Normal Irradiance
$E_{\text{incident receiver}}$ (W)	incident energy on the receiver
FF	filling factor
HTF	Heat Transfer Fluid
LFC	linear Fresnel collector
STPP	Solar Thermal Power Plants

Greek letters

ρ_{mirror}	primary mirrors reflectivity
η_{energy}	energy efficiency
$\eta_{\text{useful energy}}$	useful energy efficiency
η_{optical}	optical efficiency

There are also two plants under construction: Alba Nova-1 of 12 MW_e (France) and Kogan Creek Solar Boost, of 44 MW_e (Australia), the latter to generate superheated steam at 60 bar and 370 °C using a once-through receiver.

As seen in Table 1, all the existing LFC plants use water–steam as heat transfer fluid. There are other possible fluids being analyzed in prototypes, such as molten salt, oil or compressed air. It is difficult to assess at current time which technology is the most convenient.

Table 1
Linear Fresnel collector plants to produce electricity.

Name of the plant	Project type	Power	Receiver	HTF
Kimberlina Solar Thermal Power Plant (California, USA)	Commercial	5 MW _e	Multi-tube receiver, no secondary concentrator, non-evacuated	Water –steam
Puerto Errado 1 (Murcia, Spain)	Prototype	1.4 MW _e	Single-tube absorber with secondary concentrator, non-evacuated	Water –steam
Puerto Errado 2 (Murcia, Spain)	Commercial	30 MW _e	Single-tube absorber with secondary concentrator, non-evacuated	Water –steam
Fresdemo (Almeria, Spain)	Prototype	–	Single-tube absorber with secondary concentrator, non-evacuated	Water –steam
CNIM (Seyne-sur-mer, France)	Prototype	–	–	Water –steam
Augustin Fresnel 1 (France)	Prototype	0.25 MW _e	Single-tube absorber with secondary concentrator, non-evacuated	Water –steam
Solar boiler for Liddell power station (Australia)	Commercial	9.3 MW _{th}	Single-tube absorber with secondary concentrator, non-evacuated	Water –steam

The main drawback of water–steam is the storage and its controllability in transient conditions, especially in very long lines [13–15].

Some of the main differences among LFC plants are based on the mirror aperture width, the tracking system design, the specific mirrors curvature – flat, circular or parabolic, the solar field filling factor, the height of the receiver above the primary mirror field, and the detailed receiver design: multiple tube receiver or single-tube receiver.

1.1.1. Multi-tube receiver

The multi-tube design appears on the first prototypes and studies in LFC [16,17], although more studies and interest occurred as a result of the CLFC (compact linear Fresnel collector) development. The most conventional multi-tube design consists of a series of parallel tubes arranged horizontally in a cavity, usually with a trapezoidal cross-section and therefore without secondary concentrator. A glass cover can be located at the opening of the cavity. The primary mission of this cover, and the decision to include or not in the design, is to protect the selective coating that reduces re-radiation losses. As a secondary objective, but also important, the glass cover is responsible for some greenhouse effect that benefits receiver performance; at last, it also minimizes convection losses, due to the vacuum existing inside it. However, technical complications involved in creating vacuum in a great cavity of not elementary geometry have stimulated to research on selective coatings that can withstand ambient pressure [18]. These coatings are not yet in a commercial operation phase. Therefore, the tubes are usually not covered by a selective paint, although there are several studies that analyze the thermal behavior of the receiver with selective coating and, therefore, with a glass cover on the aperture [19–23].

The Kimberlina plant has employed a multi-tube design in the receiver [9], although there are few data about the specific characteristics of this design.

1.1.2. Single-tube receiver

The single-tube design is based on the use of only one tube (with a diameter usually in the range from 7.5 cm to 18 cm), in general, this tube is located within a cavity provided with a secondary concentrator shaped as a double parabola – Compound Parabolic Collector, CPC – and can have a glass cover at the bottom of the cavity [24–26].

There was a great interest in this single-tube design with secondary CPC reflector and without selective coating, constructing a prototype in Belgium, by the Solarmundo company [27]. Puerto Errado 1 and 2 plants [1–4], and also Fresdemo prototype [28,29] employ the single-tube technology with secondary concentrator, and without selective coating.

This is not the only single-tube configurations. New designs are considering the option of the tube coated with a selective paint and protected from environment by a concentric glass cover [30], in order to minimize radiation and convection losses, and thus to increase the fluid temperature; such fluid could be air [31,32], superheated steam [33] or molten salts [34]. In the first two cases, the receiver still has a secondary CPC reflector, with a horizontal opening. In the third design, Grena et al. suggest that, using evacuated tubes there is no need of a convection shield and the geometry of the secondary reflector is completely free; they also noted that a horizontal opening can cause a strong decrease in the optical efficiency for high zenith angles, so they proposed for the secondary reflector a geometry based on two “open-parabolic-wings”.

Even though there are many receiver designs derived from the two above concepts – multiple tube or single tube, the mirror field

design of almost all plants and prototypes constructed is based on a classical central configuration, with only one linear absorber on a single centered receiver located at certain height above the primary mirrors field. Although there are several studies trying to improve the optics of these systems [35–41], the fact is that so far, none of them has resulted in a real prototype.

Typically, for a solar field size large enough it is required to have several units in parallel as described above. In these cases, the compact linear Fresnel collector (CLFC) appears as a very attractive option [42,43]. It consists in installing one linear absorber at each side the mirror array, so that consecutive mirrors point to different absorbers. This is particularly advantageous in the case of mirrors located far from the receiver, where shading and blocking losses become important, as such losses are minimized when consecutive mirrors are nearly perpendicular. Therefore, for a given field width, a greater filling factor may be achieved without increasing these optical losses. Development of such systems began at the University of Sydney in 1993, and it was later patented [44,45]. As discussed in Section 1.2, one of the objectives of the paper will be the study of these systems compared to conventional central LFC systems.

1.2. Structure and scope of the paper

As a first step, this paper quantifies optical losses in terms of different geometrical parameters such as the receiver height and the primary mirror field width. For this sensitivity analysis, Fresdemo prototype [28] constructed in the Plataforma Solar de Almería (PSA) in Spain, has been considered. This analysis shows that the characterization cannot attempt to maximize optical or thermal performance, as it neither provides enough information about what will be the global performance of the LFC system. Therefore, a new variable is defined and optimized, the useful energy efficiency, which takes into account the radiation intensity on the receiver above a threshold, in this case 10 kW/m², since it is considered that below this intensity, useful fluid heating is very small. This first study also highlights the need for an optical analysis taking into account the specific characteristics of the receiver to be used, and it presents an optimized fluid flow layout in the receiver for the radiative-to-convective heat exchange.

Second, the article is focused on analyzing, within the framework defined in the previous paragraph, different LFC configurations proposed in the literature, taking into account the location and orientation of the receivers. Specifically, the CLFC design is analyzed, considering a horizontal receiver. Although the design with vertical receiver may be an attractive option when considering the receiver proposed by Mills and Morrison [42], the horizontal receiver configuration is taken as a reference for comparison with the “conventional” central LFC, since in this way comparison is

was decided to develop a new code, implemented in Matlab in order to provide the program of a great modularity. Therefore, complex sensitivity analysis may be carried out to identify the parameters that have a greater influence on optical losses, and new designs may be easily analyzed.

Fresnel collectors consist of a set of parallel linear mirrors focusing on the same linear receiver. Such mirrors may be flat, or have a parabolic or circular shape. For the results showed in this paper, the parabolic shape has been selected, although the two others can be easily implemented.

The program incorporates a routine that calculates the orientation of the mirrors from the sun's position at the instant considered. This routine is also capable of subsequent changes; for example, the orientation criterion is different when analyzing compact linear Fresnel collectors instead of central linear Fresnel, as discussed in the next section.

The program is able to obtain incidence angle losses, blocking and shading, and end and lateral losses. Optical and sunshape errors are also taken into account yielding to an effective sunshape [48,49]. For these analyses, sunshape is considered as a pillbox distribution of angular radius equal to 4.65 mrad. And the effective optical error cone, that is the convolution of all the optical scattering distributions, is a normal distribution according to the Central-Limit Theorem, whose dispersion, σ_{opt} , is equal to 5 mrad.

Validation of the simulation program was carried out in Ref. [50] and it is summarized in Appendix A, using the SOLTRACE code, a program developed by the National Renewable Energy Laboratory (NREL) [51]. In the validation, real data of FRESDEMO prototype [28], installed in the PSA, have been considered.

2.1. Definition of the proper framework to perform the analysis

To perform an adequate comparative analysis, it has been previously defined a proper framework and the relevant parameters to assess each of the suggested configurations.

Analyses are based on hourly data of a typical year in the PSA [52], where FRESDEMO is located. Hourly performance of the selected configurations is obtained by means of Montecarlo Ray tracing method.

The evaluation of each of the configurations is carried out by means of annual averages of the energy efficiency, the optical efficiency, and useful energy efficiency, which are defined as follows.

$$\eta_{\text{energy}}(\%) = 100 \cdot \frac{E_{\text{incident receiver}}}{\text{DNI} \cdot A_{\text{primary mirrors}}} \quad (1)$$

$$\eta_{\text{useful energy}}(\%) = 100 \cdot \frac{E_{\text{incident receiver}}(\text{Radiant flux density} \geq 10 \text{ kW/m}^2)}{\text{DNI} \cdot A_{\text{primary mirrors}}} \quad (2)$$

accomplished under the same conditions (same mirror surface pointing to the same receiver, located at the same position).

2. Methodology for optical characterization of Fresnel collectors

The optical analysis has been approached by means of a detailed Ray tracing program for Fresnel collectors. There are several Ray tracing programs reported in bibliography [46,47]. Nevertheless, it

$$\eta_{\text{optical}}(\%) = 100 \cdot \rho_{\text{primary mirrors}} \cdot \frac{\text{Rays}_{\text{incident receiver}}}{\text{Rays}_{\text{total}}} \quad (3)$$

The efficiency parameter that better provides information is the useful energy efficiency because it only accounts for the energy impinging with radiant flux density above a given threshold (10 kW/m²) to provide useful work [54].

The percentages of shading, blocking, receiver shading, end and lateral losses have also been calculated.

Table 2

Optical and geometrical data of Fresdemo prototype.

Optical and geometrical parameters of Fresdemo prototype	
Number of primary mirrors	25
Total solar field width (m)	21
Total primary mirrors length (m)	100
Primary mirrors width (m)	0.6
Primary mirrors height (m)	2
Receiver height (m)	10
Receiver width (m)	0.5
Receiver length (m)	100
Mirror axis orientation	N–S
Mirror reflectivity	0.93

For each configuration, 9 different cases have been considered, changing the receiver height and primary mirrors field total width. A change in the latter is equivalent to change the filling factor for a given number of primary mirrors, where the filling factor holds:

$$FF = \frac{A_{\text{primary mirrors}}}{A_{\text{solar field}}} \quad (4)$$

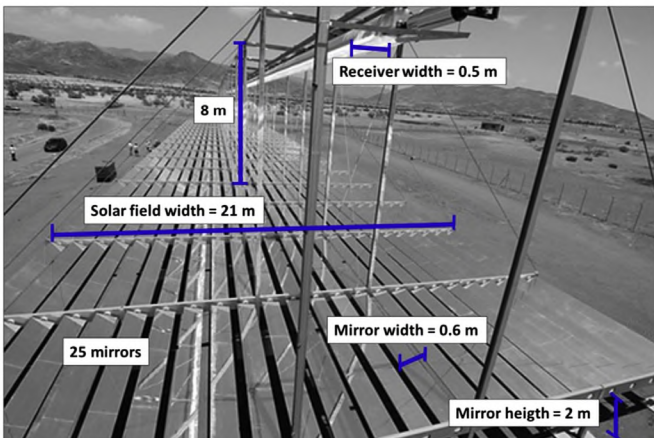
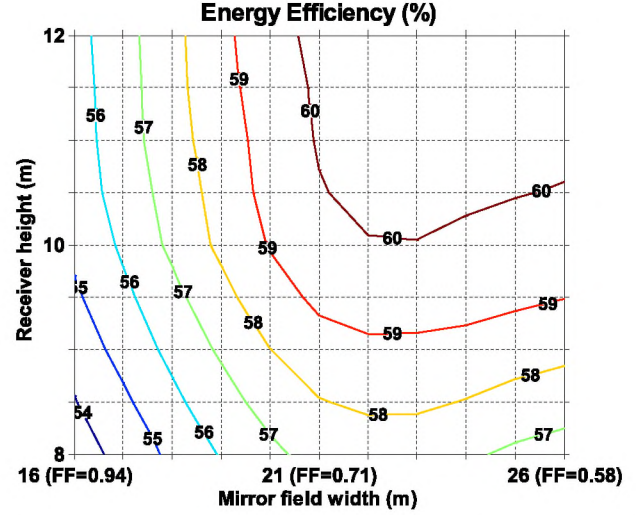
Thus, the optimum solar field width is equivalent to an optimum filling factor.

2.2. Sensitivity analysis of the optical losses in a Fresnel collector

For the first analysis, the Fresdemo configuration is considered. Optical and geometrical parameters of that prototype are showed in Table 2 and Fig. 1.

The annual performance of such LFC has been characterized, as well as 8 similar configurations, in which the total solar field width and the receiver height are varied from 16 m to 26 m, and from 8 m to 12 m, respectively (the total solar field width and the receiver height are 21 m and 10 m, respectively, for the case of Fresdemo). The primary mirrors have a certain elevation above the ground (in the case of Fresdemo, the primary mirrors are 2 m high). Changing the width of the solar field keeping the number of mirrors fix is equivalent to changing the filling factor, defined in the previous section; therefore, for the same number of mirrors, narrower fields will result in greater filling factors than larger fields.

As already said in the previous section, the annual simulation is based on one type-year data in the PSA. The calculation of the different annual averages (shading, blocking, energy, optical and useful energy efficiency) only takes into account the hours in which

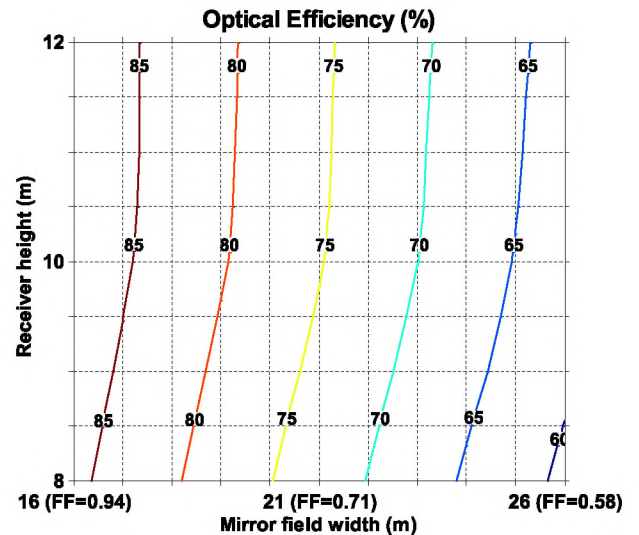
**Fig. 1.** Main geometrical parameters of FRESDEMO prototype.**Fig. 2.** Annual energy efficiency for a central LFC as a function of the mirror field width and the receiver height.

the zenith angle is between $\pm 75^\circ$, that is, sunrise and sunset hours are not accounted in the annual performance.

The annual energy efficiency is shown in Fig. 2, for the different cases considered. Similarly, Fig. 3 shows the annual optical efficiency, and Fig. 4, the annual useful energy efficiency. In the abscissa axis both the mirror field width and its respective filling factor are shown, taking into account the number of mirrors (25) and the width of each (0.6 m).

From the point of view of the annual energy efficiency (Fig. 2), the best configuration is the one that has the widest solar field (i.e., the lowest filling factor, equal to 0.58) and the highest receiver. This is because this configuration presents the lowest blocking shading annual ratios and, therefore, it achieves the greatest energy collected in the receiver for a fixed mirror surface. However, this efficiency does not take into account the concentration of the incident energy, something that the useful energy efficiency does consider, as discussed below.

Annual optical efficiency (Fig. 3) is maximized for the configuration having the narrowest mirror field (i.e., the highest filling

**Fig. 3.** Annual optical efficiency for a central LFC as a function of the mirror field width and the receiver height.

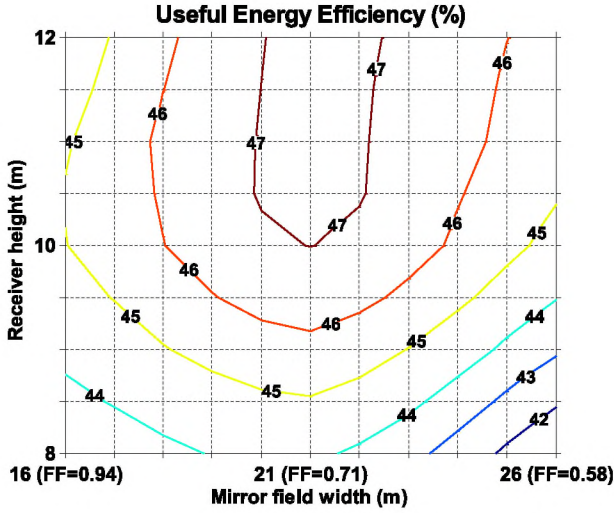


Fig. 4. Annual useful energy efficiency for a central LFC as a function of the mirror field width and the receiver height.

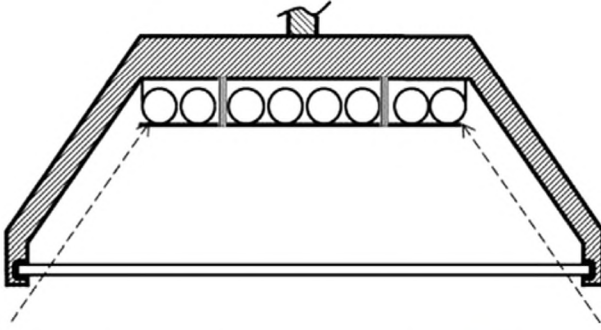


Fig. 5. Cross-section of the multi-tube receiver proposed in Ref. [53]. The preheating of the fluid that enters the receiver is performed in the lateral modules, while the same fluid at higher temperature is then heated in the central modules.

factor, equal to 0.94) and the highest receiver. In this case, due to the definition given for the optical efficiency (ratio between incident rays on the target and the total number of rays), the shading between mirrors is not penalized, as the ray is reflected by a mirror, although this mirror shades the neighboring mirrors; on the

contrary, blocking is penalized, because, in this case, the rays did not reach the target.

Finally, the highest useful energy performance (Fig. 4) is reached for a total mirror field width equal to 21 m (equivalent to a filling factor of 0.71), which is Fresdemo width. And the optimum receiver height is around 12 m – it is possible that even a little more, since no calculation is made at more height, which is a little more than Fresdemo receiver height. This efficiency gives the most comprehensive information, since it only takes into account the energy that reaches the receiver with a concentrated irradiance above 10 kW/m^2 , considering that the incident energy below this limit does not yield to an useful work (or, in this case, fluid heating).

These results highlight the importance of properly defining the optimization parameters, because certain parameters only give biased information. In the following analysis of Section 3, the useful energy efficiency is considered.

It is important to point out that it has not been considered any specific receiver design, shaping the latter as a rectangular target of 0.5 m wide and 100 m long. Nevertheless, the optical characterization of a Fresnel system must take into account the specific design of the receiver. Although it is difficult to determine that a design is better than the other, the basic characteristics of a particular receiver [53] are presented in Fig. 5. This design matches very well to the concentrated solar irradiance map in central LFC with only one central focusing line.

This design presents clear advantages by considering the specific characteristics of concentrated solar irradiance map on the absorber surface. Fig. 6 shows the concentration map (defined as the ratio between the number of incident rays per absorber surface unit area and the number of beams per sky unit area) and the concentrated solar irradiance on the receiver. These maps were obtained with the Ray tracing program mentioned in the previous section, for 100 000 rays. It has been assumed Fresdemo configuration, at solar noon on June 21st and a DNI (Direct Normal Irradiance) of 900 W/m^2 .

It can be seen in both figures that there is a clear axial symmetry with respect to the central focus axis. Although there are several studies that try to uniform the absorber surface temperature by either several lines of focusing or heat exchange inside the cavity, these designs have a negative effect on the energy and exergy efficiencies. Therefore, the proposed design attempts to arrange the fluid flow layout to the symmetry of the solar image on the absorber surface. For that, as there are one symmetry axis that divide the heat flux map in two zones, total HTF (Heat Transfer Fluid) flow is separated into two symmetrical and independent

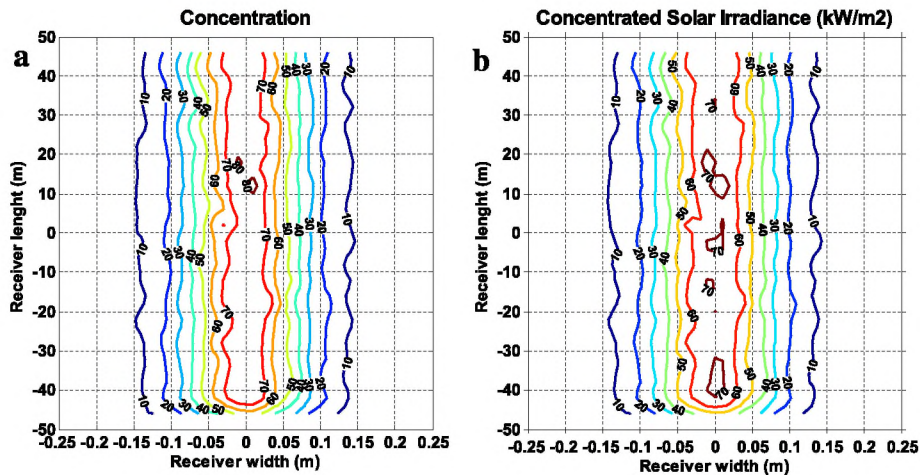


Fig. 6. Concentration map (a) and concentrated solar irradiance map (b) on Fresdemo receiver, on the 21st June at solar noon (12:00 solar time).

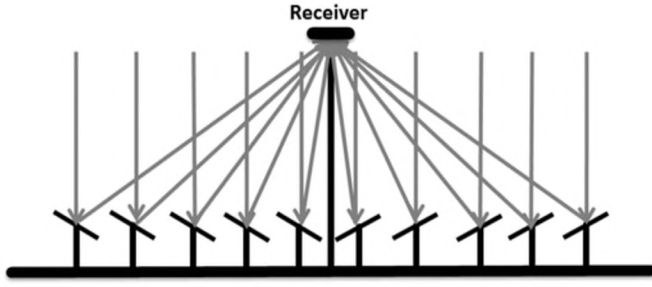


Fig. 7. Central LFC.

circuits, located in each of the two parts where the absorber surface has been divided. The main advantage of this scheme is that more uniform temperatures are achieved at the receiver outlet, because all the circuits are subjected to almost the same solar irradiance boundary conditions. As the outlet temperature of the two circuits is fairly similar, irreversibilities are reduced; thus, a higher outlet temperature is achieved for the same solar irradiance map, or the same outlet temperature can be obtained with lower incident heat flux. This last case implies lower re-radiation heat losses, resulting in better receiver thermal efficiencies.

There are specific calculations of this design concept in previous works, both applied to linear receivers [54,55] as well as to central receivers [56] – where there is also symmetry in one or two axes. Therefore, no specific calculations are presented in this section, not being the aim of the paper.

3. Comparative analysis between central linear Fresnel collectors and compact linear Fresnel collectors

This last section is devoted to a comparative analysis between the CLFC configuration and central LFC configuration. As mentioned in Section 1.1, the main advantage of the CLFC configuration versus central LFC is based on that blocking optical losses decrease drastically, thanks to the use of two receivers for each mirror array. The annual simulations show whether this advantage provides better annual performance of such systems.

The following configurations are considered: a Central LFC with horizontal receiver (Fig. 7), and two different concepts of CLFC with horizontal receiver (Figs. 8 and 9): CLFC-complete (Fig. 8), where all mirrors alternate their tilt focusing to one or another receiver; and CLFC-hybrid (Fig. 9), where only the farthest mirrors from both receivers, i.e., those located in the center of the field, alternate their tilt pointing to one or another receiver.

In order to have equivalent configurations, the orientation of the receiver has been chosen horizontal in all the cases. Besides, the

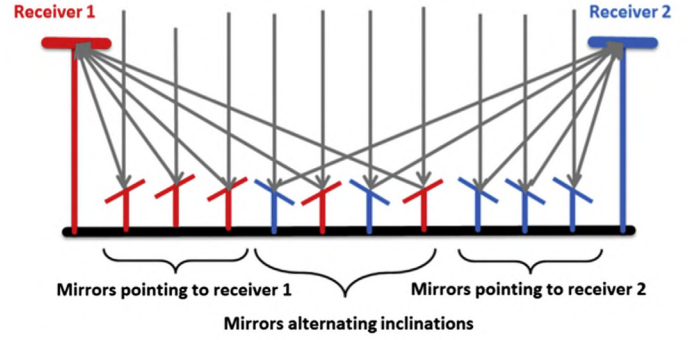


Fig. 9. CLFC-hybrid.

receiver surface must be the same, and also the primary mirror surface focusing to each receiver.

This requirement is not obvious in the case of CLFC. In the scheme observed in Figs. 8 and 9 one may observe that only half the mirrors array is focusing onto each receiver. However, one should consider that this design is thought to have many mirror arrays in parallel, so receiver 1 would receive in addition to the radiation depicted in such figures by the right side, an identical radiation as the one impinging onto receiver 2 by the left side. This is equivalent to say that the radiation flux impinging of each receiver is the sum of that impinging onto both receivers when one mirror array is simulated.

Table 3 summarizes optical and geometrical parameters selected for the configurations. These parameters are similar to those assume in Ref. [42], for a CLFC configuration with vertical receiver. The main difference is the receiver height over the mirror field, which is greater for horizontal receivers [50].

As in the comparison of Section 2.2, in this case different filling factors are also being considered since, although the field width remains constant, the number of mirrors changes between 24 (filling factor equal to 0.48) and 48 (filling factor equal to 0.96).

The aim of the CLFC concept being to reduce shading and blocking, such losses in the three configurations will be first analyzed. It should be noted that both blocking and shading imply economic losses because not all the mirror area is used. This is due either to the fact that part of the reflective surface is shaded by other mirrors (shading), or to the fact that the reflected beam from one mirror does not impinge on the receiver as it is intercepted on its way by another mirror (blocking). Fig. 10 illustrates these two effects.

For the evaluation of these two losses, the following two annual parameters have been calculated: annual ratio of shading and annual ratio of blocking, defined in Equations (5) and (6).

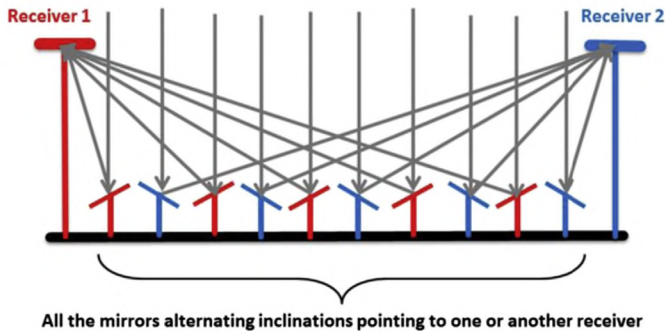


Fig. 8. CLFC-complete.

Table 3

Optical and geometrical data of the selected configurations.

Optical and geometrical parameters	LFR	CLFC-hybrid	CLFC-complete
Number of primary mirrors	24-36-48	24-36-48	24-36-48
Total solar field width (m)	50	50	50
Total primary mirrors length (m)	100	100	100
Primary mirrors width (m)	1	1	1
Primary mirrors height (m)	2	2	2
Receiver height (m)	12.5-25-37.5	12.5-25-37.5	12.5-25-37.5
Receiver width (m)	1	1	1
Receiver length (m)	100	100	100
Mirror axis orientation	N-S	N-S	N-S
Mirror reflectivity	0.93	0.93	0.93

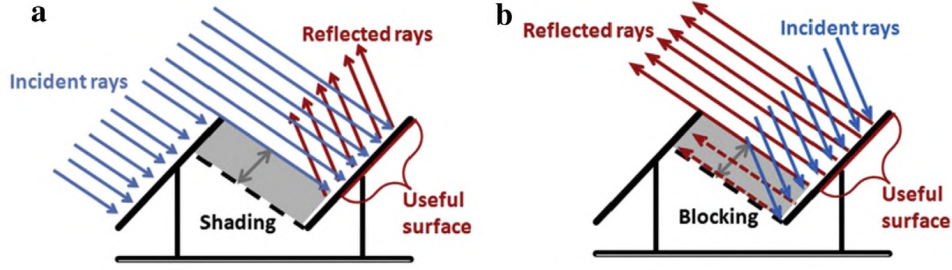


Fig. 10. Shading (a, on the left) and blocking (b, on the right) between two primary mirrors in a Fresnel collector.

$$R_{\text{shading}}(\%) = 100 \cdot \frac{A_{\text{shaded, primary mirrors}}}{A_{\text{primary mirrors}}} \quad (5)$$

$$R_{\text{blocking}}(\%) = 100 \cdot \frac{A_{\text{blocking, primary mirrors}}}{A_{\text{primary mirrors}}} \quad (6)$$

In all configurations: shading is greater for denser mirror fields (higher filling factor) and higher receivers. It is observed that the change in shading with the filling factor is greater than with the receiver height, so the gradient of variation is almost horizontal. It is also seen that both CLFC configurations result in lower annual shading, being better for the complete configuration than for the hybrid. This is due to the alternated mirror inclinations, which reduce shades between mirrors, especially in the central part of the solar field (see Fig. 11).

In the case of blocking, it is first observed that comparatively it is less important than shading, for the particular geometrical solar field parameters considered (i.e., total solar field width and receiver height). It is also observed that blocking increases as filling factor increases and receiver height decreases; in this case, the receiver height has a greater influence than in the case of shading, resulting in level straight lines tilted 45° approximately. At last, while a decrease is obtained for the hybrid CLFC compared to the central LFC, blocking in the complete CLFC is of the same order as the central LFC, even greater for some configurations, because the ratio between the mirror-receiver distance and the receiver height also increases (see Fig. 12).

According to these results, it would be expected that the best optical performance occurred in the hybrid configuration. However, as seen in Fig. 13, the central LFC is the one with higher optical performance. This is because the shading and blocking decrease

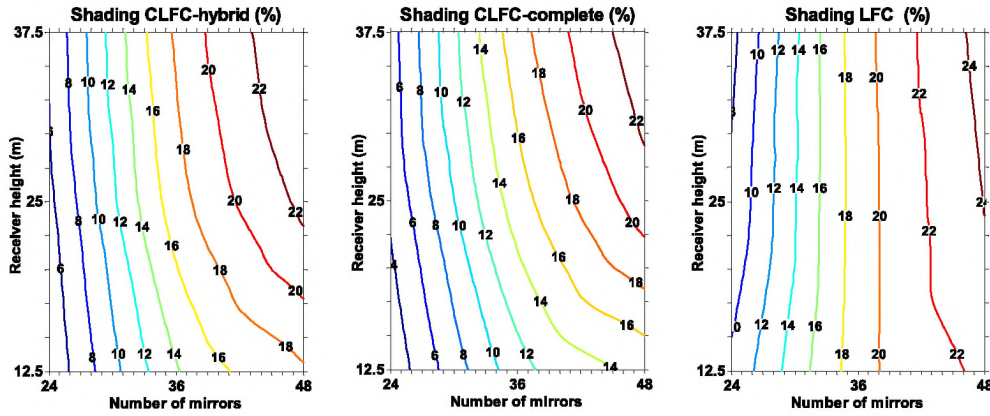


Fig. 11. Annual shading for the three configurations considered.

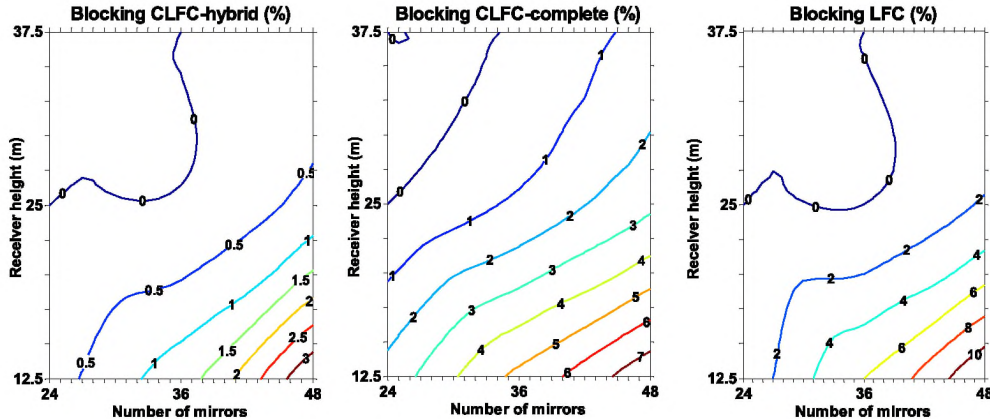


Fig. 12. Annual blocking for the three configurations considered.

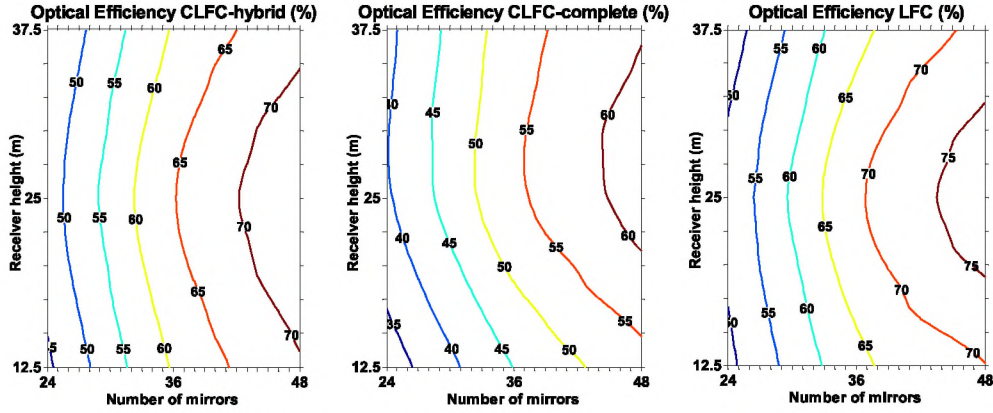


Fig. 13. Annual optical efficiency for the three configurations considered.

achieved in the CLFC respect to the center LFC do not compensate the other 3 factors influencing the optical performance, that are larger in the CLFC, namely: receiver shading, end and lateral losses. The last two effects are obvious: as the distance from the mirrors to the receiver is increased, the dispersion of the rays caused by the effective sunshape (optical and sunshape errors) is also increased. The first effect is caused by having receivers on both sides of the mirrors field: while farthest mirrors suffer minor shadows by the receiver to which they are focusing, they may suffer from adjacent receiver shading. In any case, the differences between one and another arrangement are small and, as a result, the optical performance, though slightly higher in the central LFC, is in the same order for all the configurations.

Fig. 13 shows that the optical efficiency increases for denser solar fields (i.e., higher filling factor, equal to 0.96). This is due to the optical efficiency definition given above (ratio between incident rays on the target and the total number of rays), which implies that rays falling in the gaps between two consecutive mirrors are considered as losses, while a mirror under the shade of its neighboring is not penalized, as the ray may reach the receiver after reflection in the upper mirror. Regarding to the receiver height, it should be taken into account that the lower receiver, the lower the end and lateral losses because of lower dispersion, although the blocking increases. These opposite tendencies result in the location of the maximum optical efficiency for an intermediate height, where there is an equilibrium between end losses and blocking. The height seems to have a greater role for central LFC and hybrid CLFC, as blocking effects are more important in these configurations.

From the point of view of annual energy efficiency (Fig. 14), less dense solar fields (lower filling factor, equal to 0.48) present the

best efficiency. This is because such configuration presents lower shading annual ratio and, therefore, more energy is collected in the receiver for a fixed mirror surface. As in the optical performance, there are two opposite effects to calculate the optimum receiver height: blocking, and lateral and end losses. As in the previous case, these antagonistic effects make the optimal height to be located just in the middle of the range considered, resulting that the optimum ratio between receiver height and solar field width is 0.5 for the configurations being analyzed.

Finally, annual useful energy is displayed in Fig. 15. This parameter is used to select the optimum configuration from the point of view of concentrated irradiance above a threshold, 10 kW/m^2 , as already said. In this case, the central LFC configuration presents higher useful energy efficiency because, by having the mirrors closer to the receiver, the dispersion of the rays is smaller and concentration in the receiver is higher. The arrangement most affected by the dispersion is the complete CLFC and, as seen in Fig. 15, it is the one which shows poorer performance.

While the central LFC configuration reaches the maximum in useful energy efficiency for a filling factor of approximately 0.72, in the case of CLFC, the efficiency is maximum for more compact fields, with 48 mirrors (filling factor equal to 0.96). This is precisely the aim of the CLFC: optimal configurations are achieved in more compact solar fields.

For all cases, the optimum height of the receiver is 25 m. This also yields to an important conclusion: the optimum ratio between receiver height and solar field width for horizontal receivers is 0.5. It is important to point out that this ratio is lower for the case of vertical receivers as demonstrated in Ref. [50].

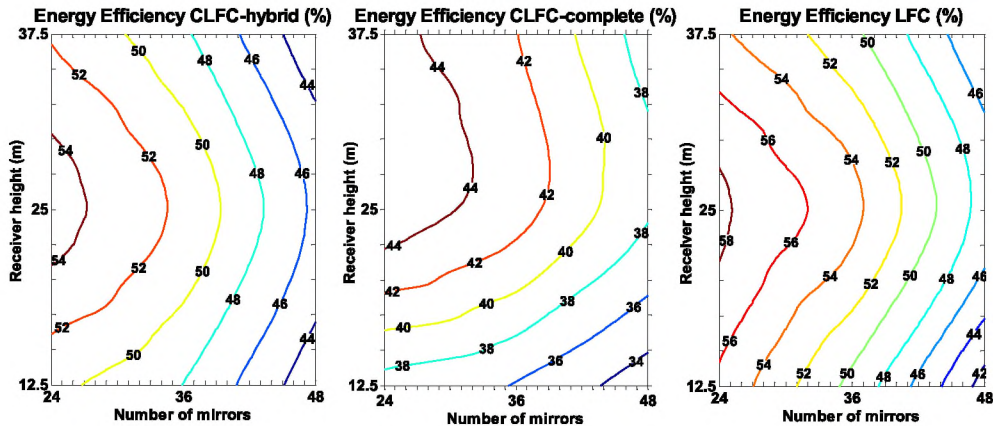


Fig. 14. Annual energy efficiency for the three configurations considered.

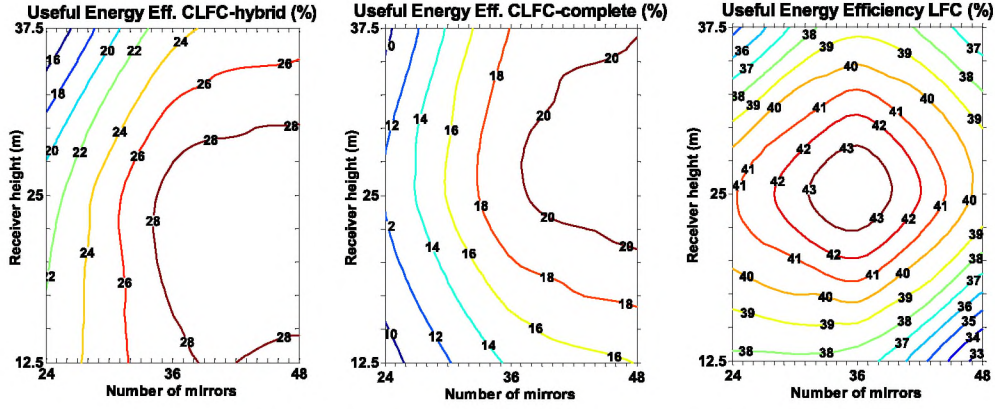


Fig. 15. Annual useful energy efficiency for the three configurations considered.

The following figures show concentrated solar irradiance map on the receiver for each of the 3 configurations analyzed: CLFC-hybrid, CLFC-complete and central LFC, for the receiver height and filling factor values that have resulted in a higher useful energy efficiency:

- CLFC – hybrid with 48 mirrors (filling factor equal to 0.96) and a receiver height of 25 m.
- CLFC – complete with 48 mirrors (filling factor equal to 0.96) and a receiver height of 25 m.
- Central LFC with 36 mirrors (filling factor equal to 0.72) and a receiver height of 25 m.

The instants chosen for the simulation are: June 21st at 12:00 solar time (Fig. 16) and the same day at 17:00 solar time (Fig. 17). The simulations have been done for 100 000 rays. Table 4

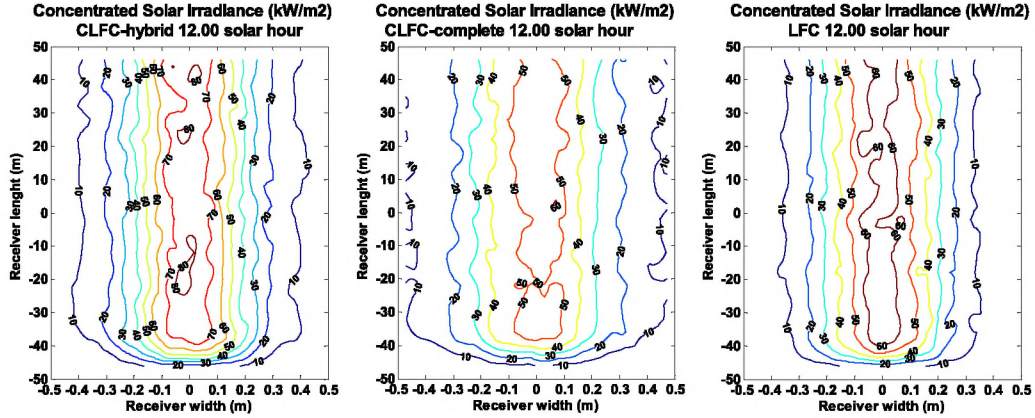


Fig. 16. Concentrated solar irradiance maps on the receiver, for the three configurations considered, on the 21st June at solar noon (12:00 solar hour).

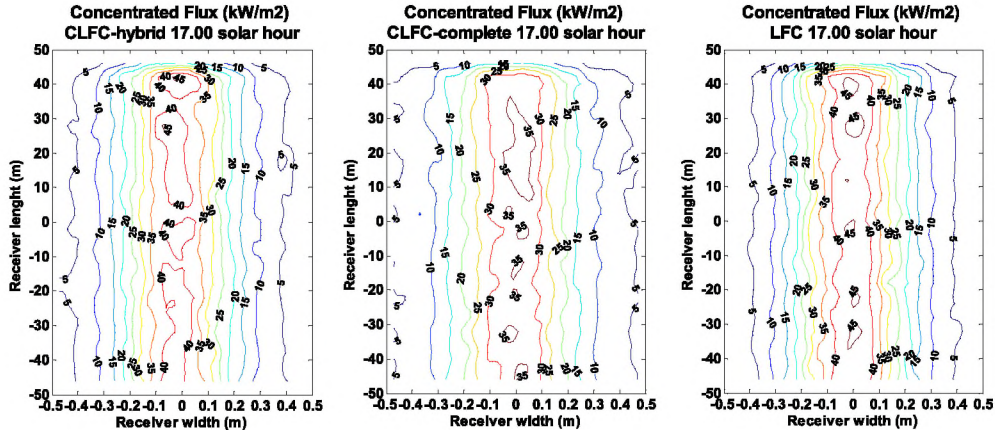


Fig. 17. Concentrated solar irradiance maps on the receiver, for the three optimized configurations considered, on the 21st June at 17:00 solar hour.

Table 4

Useful energy efficiency for the three optimized configurations considered, on the 21st June at 17:00 solar hour.

Useful energy efficiency	CLFC-hybrid	CLFC-complete	LFC
21st June at 12:00 solar hour	64.82	50.56	74.23
21st June at 17:00 solar hour	29.82	24.62	51.01

summarizes the useful energy efficiencies for each of the proposed configurations and for each point.

Fig. 16 corresponds to a point at which the sun is nearly vertical. It is observed that, for this situation the configuration CLFC-hybrid presents higher concentrated solar irradiance than the central LFC configuration. This is mainly because the filling factor of the optimal CLFC-hybrid configuration (48 mirrors in a field of 50 m wide) is higher than in the optimal central LFC configuration (36 mirrors in a field of 50 m wide). Indeed, the useful energy efficiency (Table 4) of the central LFC configuration is greater than for the CLFC-hybrid configuration, since efficiency takes into account the total primary mirrors area producing that concentrated irradiance (equation (2)).

The CLFC-complete configuration is the one with lower concentrated irradiance and lower useful energy efficiency, because the average distances from the mirrors to the receiver are higher than in the other two cases, and the dispersion of the rays is greater.

Fig. 17 shows the concentrated solar irradiance maps corresponding to a moment when the sun is tilted. It is observed that the solar irradiance values for the CLFC-hybrid configuration drop dramatically, even below the central LFC configuration. This strong decrease is also observed in Table 4: the useful energy efficiency for the CLFC-hybrid configuration falls 35 points from the solar noon to 5 h later, compared to a decrease of 23 points in the case of central LFC.

4. Summary and future work

The optical analysis of a linear Fresnel collector is a complex problem which must be properly featured before making comparisons with other devices. Efforts have been firstly aimed at the development of a Ray tracing program oriented to perform annual simulations based on hourly data. All relevant processes are studied in detail both in the incidence and reflection of solar beams on the mirrors for later concentration on the receiver. As the program has been provided with a great modularity, it is possible to easily study different mirrors field configurations and different focusing lines. These aspects have been used to study the effect of different receiver heights and filling factors, and to analyze a special configuration with two pointing receivers: the CLFC.

In addition to the development of the simulation program, a proper framework with a comparison criterion was defined. In this regard, a new variable has also been defined, the useful energy efficiency, which only accounts for the radiation that impinges on the receiver with intensities above a reference value. In a first analysis, an annual simulation for different geometries based on Fresdemo prototype has been carried out, showing that the one with higher annual useful energy efficiency is a configuration very similar to Fresdemo.

It has also been found that a complete optical characterization must take into account the specific design of the receiver because, contrary to what happens in parabolic trough collectors, this receiver admits multiple configurations, and the choice of one or another can result in significant differences in the overall

performance. In that sense, it is explained a receiver design concept, which optimizes the heat transfer in the absorber surface.

In last section, a comparative study between LFC and CLFC has been performed. Within CLFC configurations, two configurations have been considered: a hybrid CLFC in which the nearest mirrors to each of the receivers exclusively point to that receiver, while further mirrors alternate their inclination pointing to one or another receiver; and a complete configuration, in which all mirrors alternate the aiming point to one or another receiver.

It has been found that both CLFC configurations reduce blocking and shading losses compared to the central classical configuration. However, such decrease does not compensate for other geometric losses, such as end and lateral losses, which make CLFC configurations present an optical and energy efficiency lower than those of the central LFC. This configuration is also the one with the highest useful energy efficiency as it is benefited by having the mirrors closer to the receiver than the configurations CLFC, thus having less dispersion losses. For central LFC configuration, the maximum useful energy efficiency is located at a filling factor of 0.72, approximately, whereas in CLFC, this maximum moves to denser fields with a filling factor of 0.96. This is precisely the aim of the CLFC: getting more efficient compact fields.

The results of this study lead to two lines of research, both being already studied by our research group: first, the particular design and optimization of the solar receiver, with the design guidelines outlined in this article and on the other hand, a specific optical multi-objective optimization of the central LFC.

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Appendix A

The simulation Ray tracing program has been validated using the SOLTRACE code [51]. SOLTRACE is a Ray tracing program developed by the National Renewable Energy Laboratory (NREL). The main advantage of this program is that it is very general and can be used to analyze complex optical systems. The main drawback is that it does not calculate automatically the orientation of the mirrors as the sun position changes, but these mirror positions must be specified by the programmer. For this reason a particular instant has been selected for comparison, on 21st June at 12:00 solar time, at the location of the Plataforma Solar of Almeria (PSA) (latitude = 37°5'27.6"N; longitude = 2°21'19.01"; altitude = 366 m). Real data of FRESDEMO prototype [28], installed in the PSA, have been considered, as showed in Table 2, Section 2.2.

For the simulation the sunshape error has been considered as a pillbox of angular radius equal to 4.65 mrad; no optical errors have been considered for this comparison.

It is also important to point out that the receiver has been assumed as a rectangle of 0.5 m wide and 100 m length. So, neither optical nor thermal losses in the receiver are considered, as the study is focused on the optical and geometrical losses in the radiation concentration process (shading and blocking, end and lateral losses, and mirror reflection losses).

The following graphs show the impacts on the receiver, obtained by Soltrace and our Ray tracing program, for 100 000 rays.

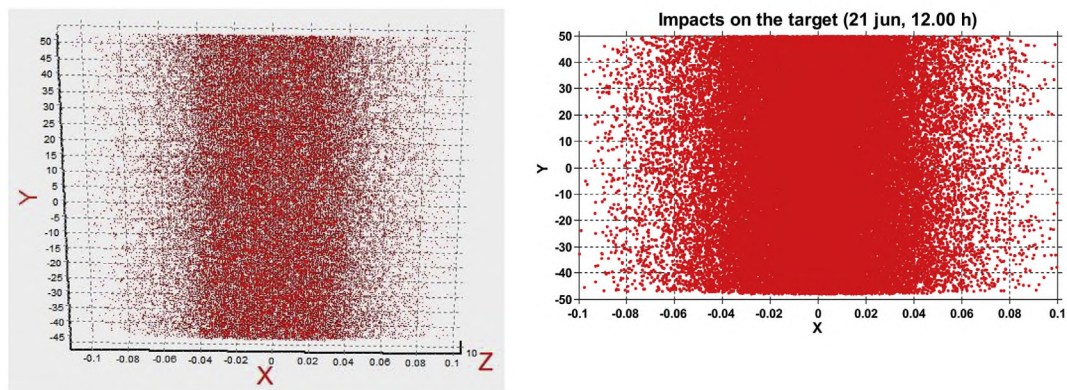


Fig. A.1. Impacts on the target: Soltrace program on the left, and own development Ray tracing program, on the right.

Table A.1 summarizes other optical parameters obtained for both programs, showing a great agreement between them.

Table A.1
Optical simulation results.

Optical results	Soltrace	Raytracing program
Concentration peak (suns)	157.9	156.88
Mean concentration	60.47	62.48
Optical efficiency (%)	60.67	60.71

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